Extraction of Doppler Observables from Open-Loop Recordings for the Juno Radio Science Investigation

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Overview

Agenda

1. Juno Mission Overview
2. Gravity Science at Jupiter
3. Instrumentation
4. Signal Processing of Open-Loop Recordings
5. Performance and Results
6. Conclusion

Team Members

Jet Propulsion Laboratory – Pasadena, CA
- Bill Folkner, Gravity PI
- Instrument Engineering
  - Dustin Buccino, Instrument Operations Lead
  - Danny Kahan, Instrument Operations
  - Oscar Yang, Instrument Operations
  - Kamal Oudrhiri, Planetary Radar and Radio Science Supervisor
- Advanced Water Vapor Radiometer
  - Elias Barbinis, Meegyeong Paik, Scott Bryant
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Southwest Research Institute – San Antonio, TX
- John Anderson, Gravity Co-I

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- Paolo Tortora

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- Andrea Miliani

Thales Alenia Space – Rome, Italy
- Lorenzo Simone, Ka-band Translator

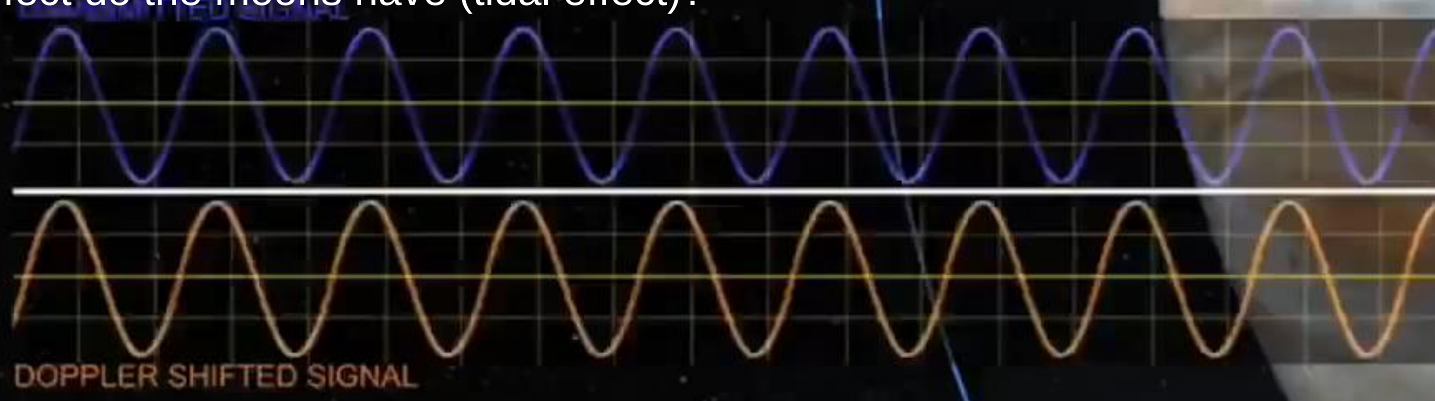
Juno Mission

- First outer-planet solar powered mission
- 53-day polar elliptical orbit designed to minimize radiation exposure
  - Launch: August 2011 (5 year cruise)
  - Orbit Insertion: July 2016
- Suite of ten science instruments to investigate Jupiter's:
  - Interior
  - Atmosphere
  - Magnetosphere

Bolton, et al, *The Juno Mission*, Space Science Reviews 213, 2017

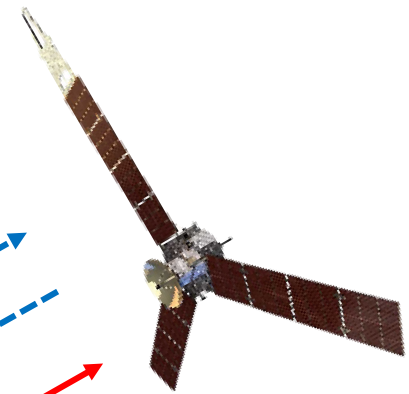
Gravity Science

- Examine changes in phase/**frequency** between the ground-based receiving stations of the NASA Deep Space Network and the Juno spacecraft to determine:
  - Mass/density
  - Spherical harmonics (gravitational field)
    - Lower-degree terms: oblateness, rotational axis, deep interior structure
      - Is there a core?
      - How deep are the winds (differential rotation)?
      - What effect do the moons have (tidal effect)?

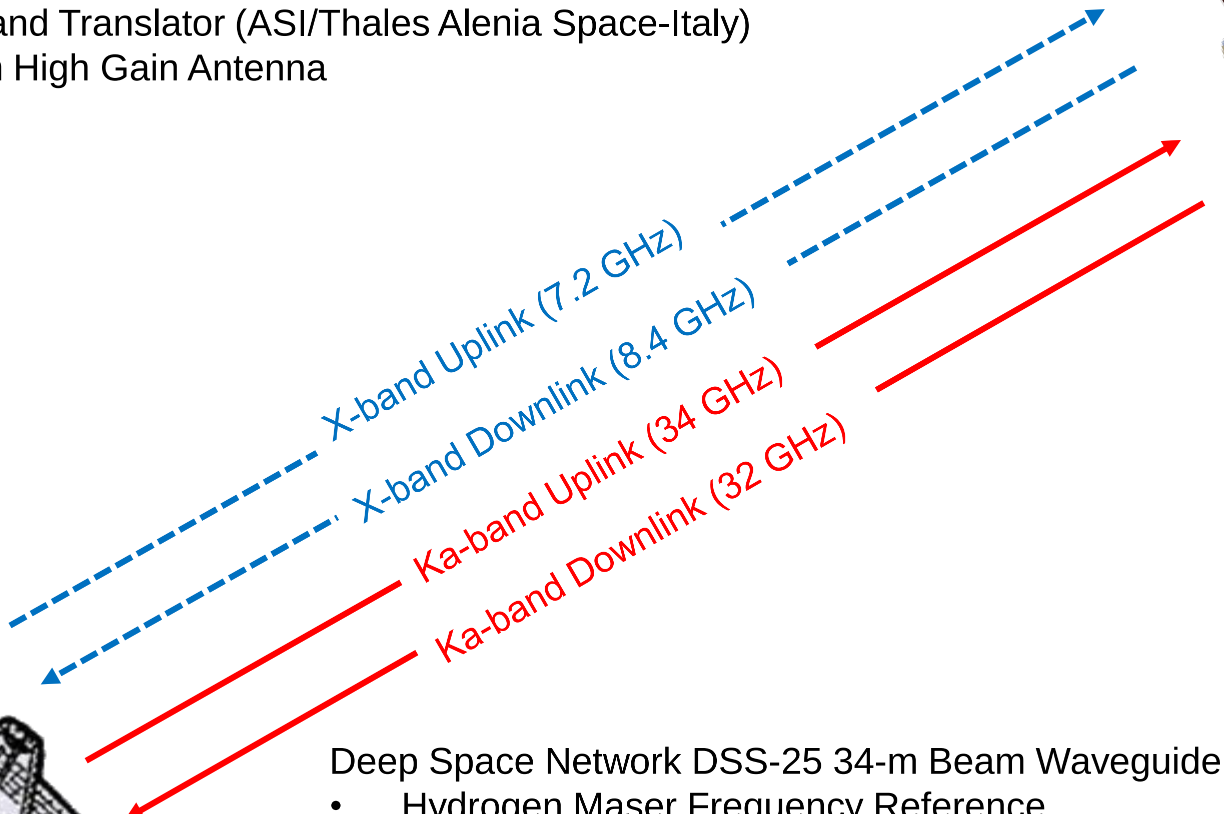


Asmar, Bolton, Buccino, et al, *The Juno Gravity Science Instrument*, Space Science Reviews 213, 2017 https://www.youtube.com/watch?v=ulzq_mIU-fA

Gravity Science Instrument



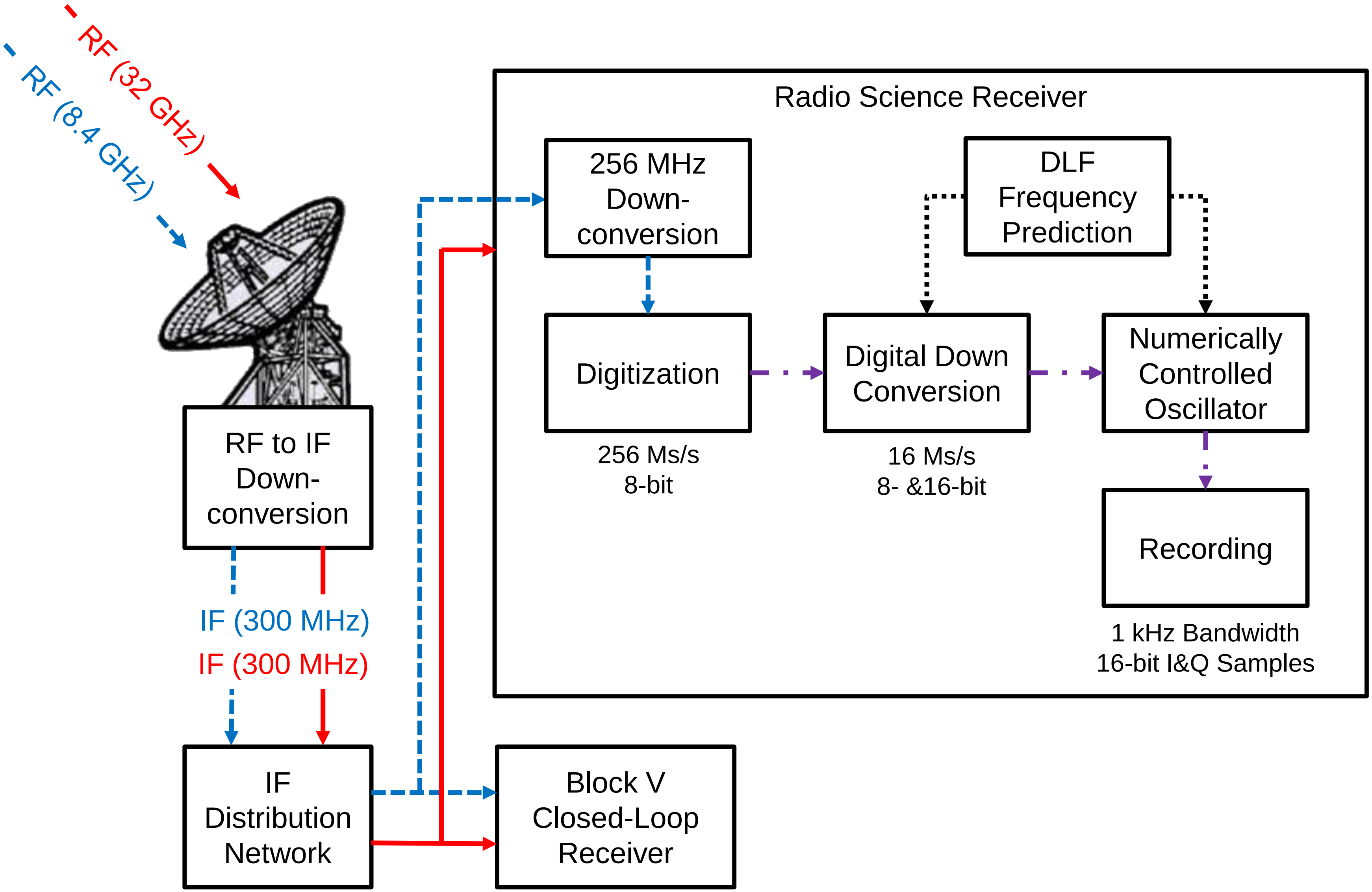
Juno Spacecraft
- X-band Transponder (Small Deep Space Transponder, JPL)
- Ka-band Translator (ASI/Thales Alenia Space-Italy)
- 2.5-m High Gain Antenna



Deep Space Network DSS-25 34-m Beam Waveguide Antenna
- Hydrogen Maser Frequency Reference
- 18 kW X-band Klystron Transmitter
- 0.3 kW Ka-band Solid State Transmitter
- Closed-Loop and Open-Loop Receivers @ X- and Ka-band
- Advanced Water Vapor Radiometers

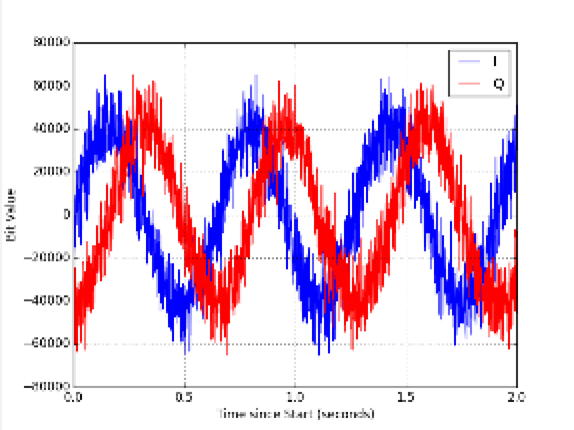
Asmar, Bolton, Buccino, et al, *The Juno Gravity Science Instrument*, Space Science Reviews 213, 2017

Open-Loop Recordings

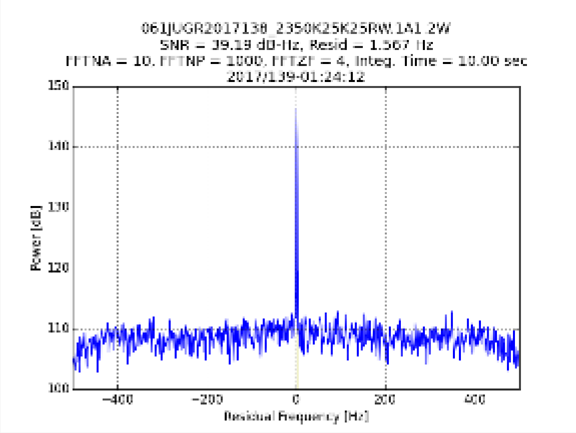


Signal Processing – Current Standard

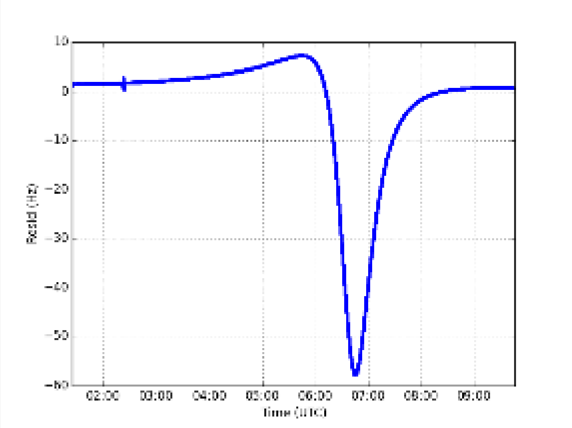
IQ Values (Recording)



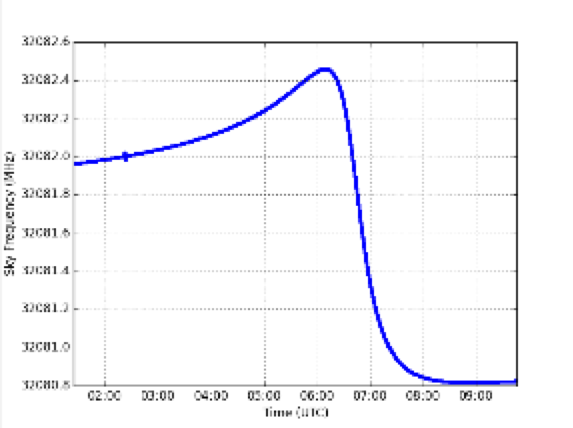
FFT – Initial Frequency Estimate



2nd Order PLL – "Residual" Frequency



Sky Frequency



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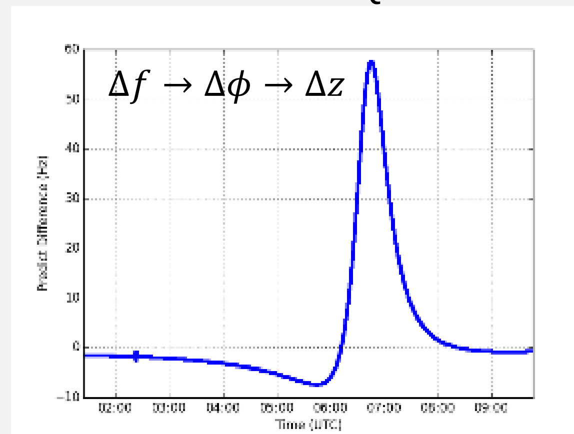
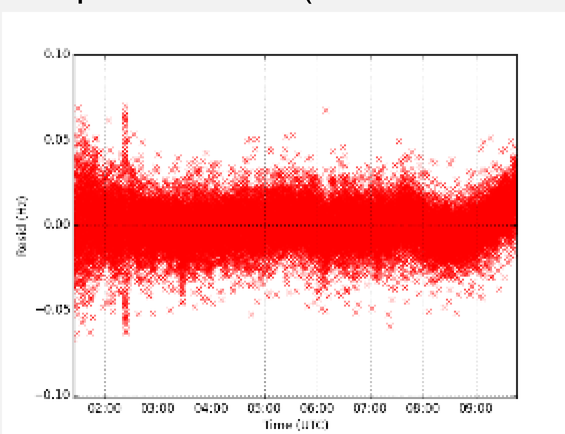
Signal Processing – New Techniques for Juno

Orbit Determination

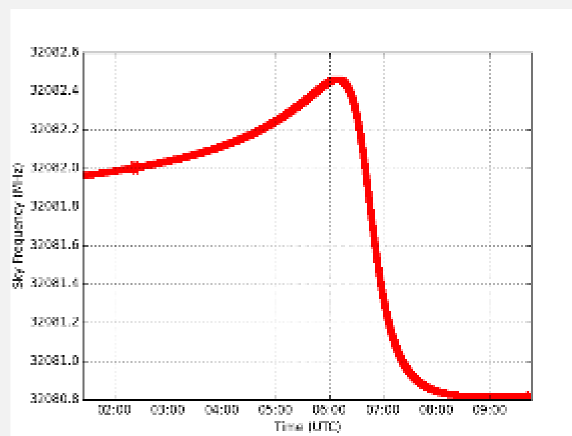
Counter-rotate IQ Values



Final Optimized PLL ("White Residuals")



Final Sky Frequency ("Observables")



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Thermal Noise Optimization

- Thermal noise contribution to Doppler error:

$$\sigma_f = \frac{\sqrt{2\boxed{B_L}}}{2\pi \boxed{T_c}\sqrt{Pc/No}}$$

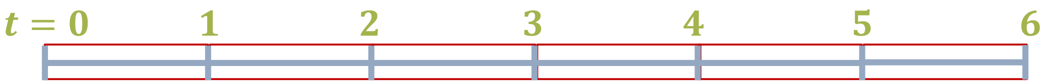
PLL Loop Bandwidth

Integration Time/Count Time

- Is optimized when:

$$B_L = \frac{1}{2T_c}$$

T_c = 10 s → B_L = 0.05 Hz
T_c = 1 s → B_L = 0.5 Hz
T_c = 0.1 s → B_L = 5 Hz



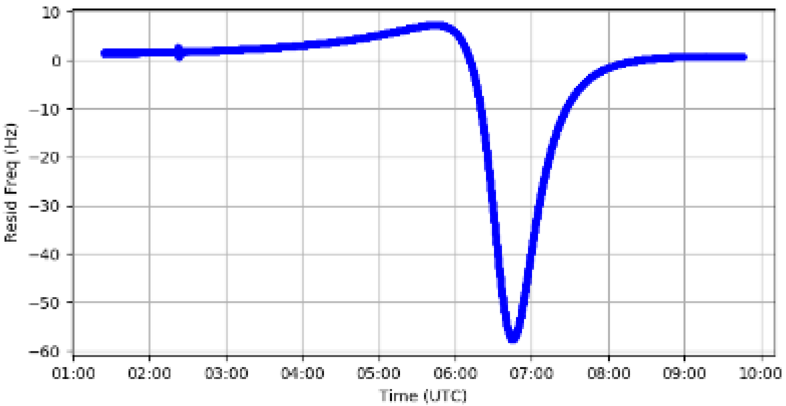
Performance and Results

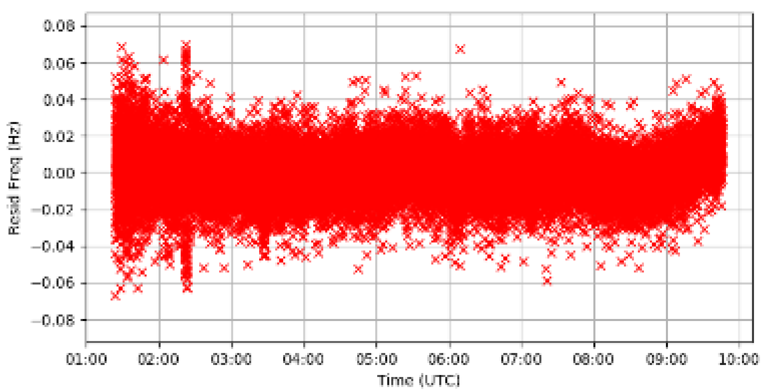
- **Goal:** Counter-rotate IQ Values to remove systematic effects for optimal phase-locked loop processing

- **Effects In Consideration:**
  - Spacecraft trajectory
  - Troposphere Delay
  - Ionosphere Delay
  - Solar Plasma/Io Plasma Torus
  - Ground Station Biases
  - Spacecraft Transponder Delay

- By counter-rotating the IQ values, we are able to obtain a ~50% reduction in noise in the residual frequency

PLL Run	RMS (Hz)
First-run (B_L = 3 Hz, T_c = 1s)	25.1 mHz
Post counter-rotation (B_L = 0.5 Hz, T_c = 1s)	12.9 mHz





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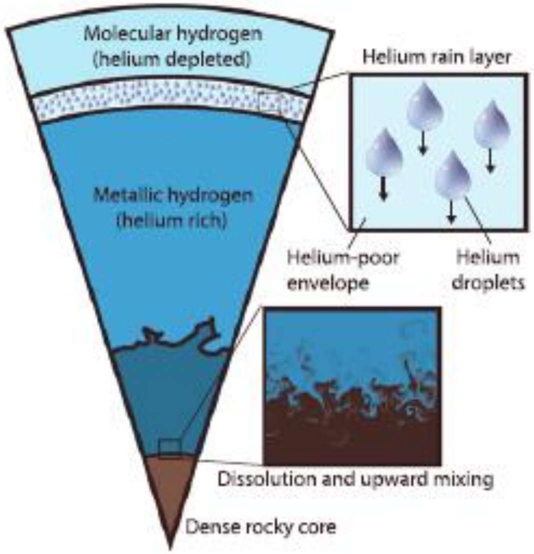
Initial Results from the Gravity Investigation

- Doppler Observables computed with the technique presented provide the input for determination of Gravitational Field Parameters
- Gravitational Field Parameters are a spherical harmonics expansion of the gravity potential

$$U = \frac{\mu}{r} - \frac{\mu^*}{r}\sum_{l=1}^{\infty}\left(\frac{a_e}{r}\right)^l P_l(\sin\phi)J_l + \frac{\mu^*}{r}\sum_{l=1}^{\infty}\sum_{m=1}^{l}\left(\frac{a_e}{r}\right)^l P_{lm}(\sin\phi)[C_{lm}\cos m\lambda + S_{lm}\sin m\lambda]$$

- First two orbits estimate the gravity field to Degree 8
- Factor of 5 improvement from previous measurements of the gravity field
- Analysis of the first two perijove passes has suggested that Jupiter’s core is diluted



Folkner et al, *Jupiter gravity field estimated from the first two Juno orbits*, GRL 44, 2017
Wahl et al, *Comparing Jupiter interior structure models to Juno gravity measurements and the role of a dilute core,* GRL 44, 2017

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Conclusion & Future Work

- Juno Radio Science Team has developed a technique to process open-loop recordings collected in a high dynamic environment into high-precision Doppler observables

- Apply this technique to other missions – are there any major improvements?
- Tools and programs largely segmented – work on merging/automation
- Possibility to extract telemetry from the open-loop recordings
  - Service currently provided by closed-loop receivers; open-loop can be used in the event of an anomaly or as a backup in a critical event

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